WORLDSID RESPONSES IN OBLIQUE AND PERPENDICULAR POLE TESTS

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ABSTRACT

The International Harmonized Research Activities (IHRA) Side Impact Working Group is proposing a 15-degree oblique pole test as part of a comprehensive side impact evaluation protocol. Since collision data from around the world indicate that young males are overrepresented in single vehicle collisions into fixed objects (women tend to be over-represented in vehicle-to-vehicle crashes), a side impact anthropometric test device representative of a 50th percentile adult male is believed to be the most appropriate dummy size to evaluate the protective capabilities of vehicles subjected to pole impacts.

In support of the IHRA Side Impact working Group activities, Transport Canada conducted a series of paired vehicle tests to compare the responses of WorldSID in 15-degree oblique pole tests to those observed in a perpendicular pole test. Vehicles included small North American vehicles equipped with head-thorax seat mounted side airbags and mid-size and SUVs equipped with both seat mounted thorax airbags and curtain technology.

While the oblique test configuration tended to result in more elevated responses a number of test parameters including side airbag deployments, dummy arm kinematics and dummy position were found to significantly affect dummy responses. WorldSID performance and thoracic measurement sensitivity in the oblique loading environment observed in the 15-degree pole test are discussed and compared to that of the ES-2re.

INTRODUCTION

The Transport Canada Side Impact Research Program was initiated in 1999 to identify factors contributing to serious injuries among women involved in vehicle-to-vehicle side impact crashes and to evaluate the appropriateness of new barrier designs and crash configurations. In the latter half of 2003 members of the IHRA Side Impact Working Group (SIWG) identified that laboratory data comparing oblique to perpendicular pole impacts were needed to help the SIWG define a harmonized test protocol for pole impacts that could be scientfically corroborated. Transport Canada began a pole test program in 2004 to compare the effects of oblique and perpendicular strikes. This paper presents the results of three paired oblique and perpendicular pole impacts conducted with the 50th percentile world harmonized side impact dummy, WorldSID. Two additional paired oblique pole tests, carried out to compare the response of the WorldSID and ES-2re in oblique pole testing conditions, are presented. Given the preliminary character of these results, parameters to be monitored and recommendations for further testing are discussed.

METHODOLOGY

Vehicle Selection

Three different model year 2004 vehicle types were selected for the comparison. These included a small North American 4-door sedan with seat mounted combination (head/ thorax) side airbags identified as ‘model A’; a mid-size Japanese 4-door sedan with seat mounted thorax side airbags and curtain identified as ‘model B’ and a European SUV with seat mounted thorax side airbags and curtain identified as ‘model C’. Vehicles selected for the WorldSID and ES2-re comparison included two model year 2003 vehicles identical to ‘model A’ but without side airbags and two small 4-door German sedans equipped with seat mounted thorax airbags and curtains and identified as Model 'D'. The test matrix is presented in Table 1.

Table 1: Test Matrix

Vehicle	Test Mass kg	Impact Angle	
		90º	15º
Model A	1427	WS	
Model A	1427		WS
Model B	1642	WS	
Model B	1662		WS
Model C	2521	WS	
Model C	2520		WS
Model A '03	1429		WS
Model A '03	1430		ES2-re
Model D	1752		WS
Model D	1772		ES2-re

Data Acquisition and Videography

The WorldSID dummy instrumentation included a nine accelerometer cluster in the head; a 6-axis load cell at the upper and lower neck; an **I**nfra**R**ed **T**elescoping **R**od for **A**ssessment of **C**hest **C**ompression (IRTRACC) (Rouhana, 2002) at the shoulder, each of the three thoracic and two abdominal ribs; tri-axial accelerometers at the upper, mid and lower spine and pelvis; accelerometers at each rib and on the spine box opposite each rib; and single axis load cells at the acetabulum, pubic symphysis and iliac.

The ES-2re included a tri-axial accelerometer at the head CG; a 6-axis load cell at the upper and lower neck; a linear potentiometer at the shoulder and each of the three thoracic ribs; tri-axial accelerometers at the upper, mid and lower spine and pelvis; accelerometers at each rib and on the spine box opposite each rib; and single axis load cells at the acetabulum, pubic symphysis and iliac.

All data recording and filtering was performed in accordance with SAE J211. Collisions were filmed at 1000 frames / second from multiple views.

Dummy Positioning

The WorldSID and ES-2re were both positioned in the driver seat as per the University of Michigan Transportation Research Institute (UMTRI) procedure, now referred to as the IIHS/UMTRI seating procedure. This procedure places the dummy in a seat track location and in a seat orientation believed to be statistically representative for a mid-size male and just forward of the B-pillar [2]. A common seating procedure was required for both dummies to facilitate comparison. Precautions were taken to ensure that the outboard arm was in place at 45º to the spine prior to impact.

Vehicle Preparation and Launch

Uni-axial accelerometers are generally installed in the driver-side door sill, in the four quadrants and centre of the driver door, at the base of the B-pillar and at the side rocker panel on the passenger side. A tri-axial accelerometer is installed at the vehicle centre of gravity. The driver-side window is taped to prevent glass splatter from interfering with camera views.

The tires are removed and the wheels placed on small trolleys as shown in Figure 1. The vehicle is aligned with the dummy head CG and launched at 29 km/h for perpendicular impacts. The 15º oblique impacts are aligned through the driver's head cg and launched at 32 km/h.

Figure 1: Photo of test set-up.

RESULTS BY TEST CONFIGURATION

Airbag Performance There were two incomplete deployments of the seat mounted head torso airbag in model 'A'; one instance of a curtain deploying behind the B-pillar trim in the perpendicular impact of model 'C' and one occurrence of punch through during the oblique impact of model 'B'. In both the perpendicular and oblique modes, the head thorax bag became entrapped by the intruding door trim and was deviated rearwards behind the driver seat. Timing during the perpendicular crash was such that the upper portion of the bag had just enough inflation to cradle the neck as the head rotated outboard and to prevent head contact with the pole. During the oblique crash, the impact point was 128 mm forward of the perpendicular impact point and though the bag became entrapped in a similar way, it was ineffective in preventing the head from striking the pole. Given the airbag deployment problems in the perpendicular mode, it is likely that the impact point alone (independent of the angle) affected the dummy head kinematics.

In model 'B' there were no problems with deployment path or timing; however punch-through occurred because the head impact was centered on a seam between two fully inflated chambers. Again, the more anterior impact point, located 132 mm forward of the perpendicular target affected the head trajectory.

Incorrect deployment of the curtain as observed in the perpendicular test of model 'C' has also been observed in other testing involving the IIHS barrier. It would appear that early onset deformation of the roofline causes disruption of the interior roof and/ or B-pillar trim leading to entrapment of the curtain. It was not possible to accurately compare deployment timing in oblique and perpendicular modes due to instrumentation and measurement limitations. Unlike frontal or seat mounted airbag openings, which can be accurately tracked with a simple filament switch the length of the curtains and variety of deployment patterns preclude the use of these non-intrusive methodologies.

At present it is not possible to employ more accurate techniques without tampering with the trim and electrical conduits. The extent to which deployment timing is affected by the pole impact angle is therefore not quantifiable at this time.

The results for the vehicle acceleration and intrusion profiles are presented first and followed by the WorldSID responses.

Vehicle accelerations for the center of gravity of the vehicle are presented in Figures 2 through Figure 4. It should be noted that the oblique configuration was characterized by higher impact energies: model 'A' was exposed to approximately 3% more energy in the oblique test; model 'B' to approximately 10% more energy and model 'C' had 5 % more energy in the oblique test.

Acceleration comparisons could only be carried out for models 'B' and 'C'. During the oblique test of model 'A' the undercarriage of the vehicle was struck by the towing cables causing eroneous measures to be recorded in all 3 axes.

Longitudinal accelerations at the cg of model 'B' and 'C' were not significant. As illustrated in Figure 2, the longitudinal component of acceleration during the first 22 msec of pole crush in the oblique loading condition was of the order of 3 g, indicating that there was very limited forward motion of the vehicle. In comparison, the perpendicular test vehicle acceleration trace displays a flat profile until structural deformation of the vehicle has been initiated.

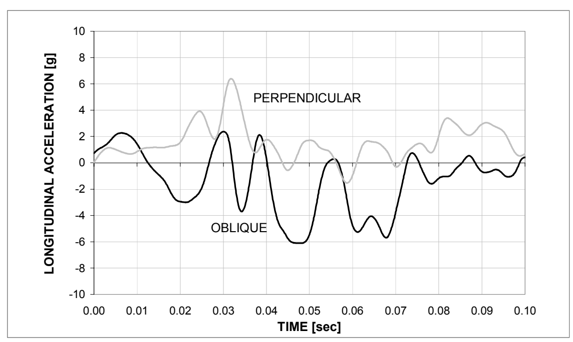

Figure 2: Longitudinal acceleration traces at the CG of Model 'B' for the two test conditions.

Lateral accelerations for model 'B' in the two test conditions are shown in Figure 3. The oblique pole test trace displays a 10 msec delay in onset compared to the perpendicular test and a greater magnitude reflective of the increased energy associated with this impact.

A comparison of the vertical acceleration components for Model 'B' is presented in Figure 4. Vertical accelerations were more prominent in the oblique test condition. This was observed for both Models 'B' and 'C' where peak vertical accelerations were of the order of 21 to 23 g in oblique compared to 9 to 10 g in the perpendicular mode.

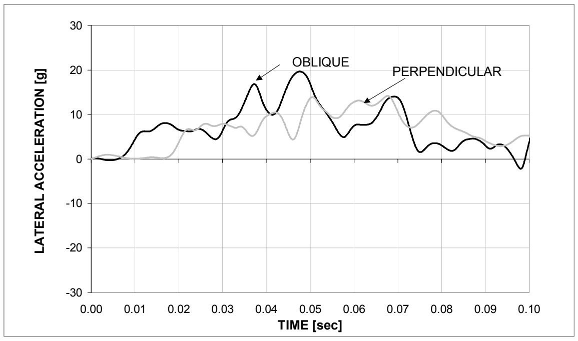

Figure 3: Lateral CG acceleration traces for Model 'B' in the two test conditions.

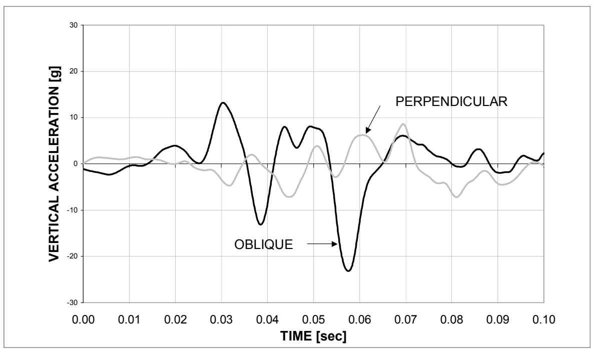

Figure 4: Vertical CG acceleration traces for Model 'B' in the two test conditions.

Vehicle intrusion patterns measured at the mid-door are shown for Model 'B' in a full size plot in Appendix A. The impact point for the perpendicular pole impact is aligned with the WorldSID lateral head CG and is located approximately 100 mm forward of the B-pillar. In the oblique alignment the target impact point was obtained by passing a plane through the true CG of the head at a projected angle of 15 degrees; placing the actual impact point 135 mm forward of the perpendicular impact point or 235 mm forward of the B-pillar. Peak intrusion at the mid-door for 'Model 'B' in the oblique mode attained 450 mm compared to a peak intrusion value of 410 mm in perpendicular. The oblique intrusion pattern was shifted some 100 mm forward of the perpendicular intrusion trace. The intrusion profiles were similar for all three model types. The oblique pole always resulted in greater intrusion where peak intrusion at the mid-door ranged from 352 to 431 mm for Model 'C' and 'A' respectively. In contrast, peak intrusion for the perpendicular mode ranged from 310 mm for Model 'C' to 361 mm for 'Model 'A'

WorldSID responses are presented for the head, thorax and abdomen. The elevated head accelerations observed for the oblique tests and shown in Figure 5 were due to the punch through that occurred with the Model 'B' curtain and the unsuccessful deployment of the seat mounted combination airbag in Model 'A' described earlier. Since both curtain and seat mounted airbag entrapment have been observed in IIHS tests and in SUV-to-car tests the inflation problems illustrated here can not readily be attributed entirely to impact angle. Given the insignificant longitudinal component of acceleration detected in the vehicle it is assumed that the forward motion of the head, defined by the longitudinal head acceleration trace illustrated in Figure 6, was due to the shift of the pole impact point, 132 mm forward, rather than the 15 degree impact angle. This forward displacement of the head towards the pole was sufficient to cause the head to impact a seam in the curtain located 20 mm beyond the fully inflated section impacted during the perpendicular crash.

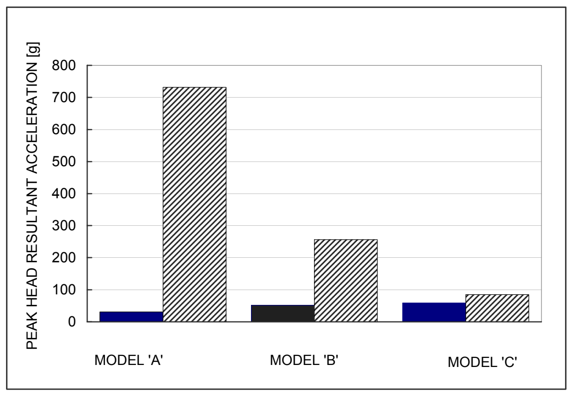

Figure 5: Peak resultant head acceleration for the WorldSID in three paired tests perpendicular and oblique.

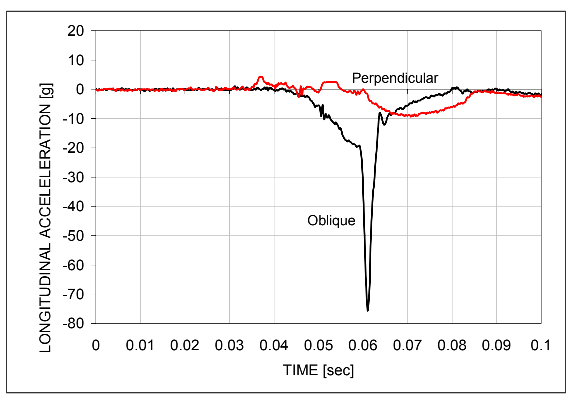

Figure 6: Longitudinal component of the WorldSID head acceleration in Model 'B'.

The WorldSID shoulder, thorax and abdominal peak rib deflections for models 'A' 'B' and 'C' are presented in Figures 7 though 9 respectively. Deflections were generally higher in the oblique pole impacts than in the perpendicular impacts. Shoulder and rib 1 deflections were twice as high in the oblique condition for both Model ‘A’ and ‘B’; while the increase in deflections for the remaining thoracic and abdominal ribs was greatest in the oblique test of model ‘B’.

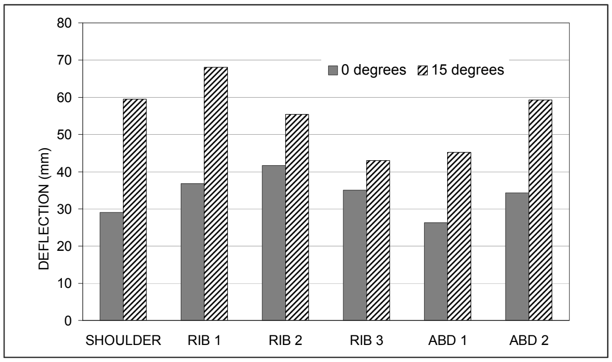

Figure 7: WorldSID thorax and abdominal responses for Model 'A'.

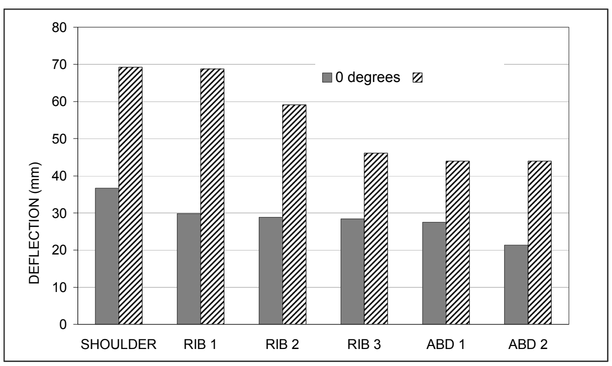

Figure 8: WorldSID thorax and abdominal responses for Model 'B'.

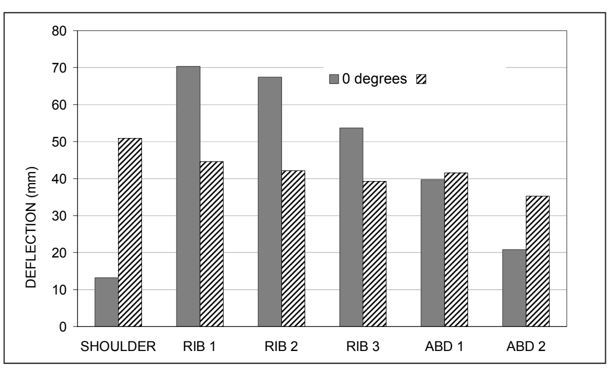

Figure 9: WorldSID thorax and abdominal responses for Model 'C'.

In the Model ‘A’ perpendicular test a peak deflection of 42 mm was recorded at the second thoracic rib dropping off on either side at rib 1 and rib 3 and rising again slightly in the second abdominal rib. In the oblique mode the loading pattern was similar however, the peak deflections were greater, 68 mm and were localized at rib 1. The seat mounted airbags in models ‘A’ and ‘B’ became entrapped by the door trim and could not be seen interacting with the driver in any camera view. They are therefore not considered to have influenced the deflection pattern of the thorax to any great extent.

The airbag performance and dummy kinematics observed in Model ‘C’ were quite different than the outcomes recorded for the other 2 models. In the perpendicular mode the seat mounted airbag was not obstructed and had sufficient force to rotate the driver arm upwards just high enough for the intruding door to dislodge the shoulder and arm complex into the window opening, further exposing the chest to the intruding structure. In the oblique mode, the thorax airbag initiated arm rotation as well, however the motion of the arm was stopped when the intruding door structure, now more forward, entrapped the arm and the shoulder. The shoulder became wedged in the rear lower corner of the window trim.

Examination of remaining responses including T1, T4 and T12 accelerations indicated that the peak values in all three axes were all greater in the oblique mode with Model ‘C’ being the exception.

RESULTS BY TEST DUMMY

WorldSID (WS) and ES-2re comparison in Oblique Test Conditions is based on two vehicle models which included a pair of 2003 Model ‘A’ vehicles without side airbags and a pair of 2004 Model ‘D’ vehicles equipped with both curtain and seat mounted airbags.

The dummies were seated using the same seating procedure as described for the previous analysis except that special attention was given to matching key landmark locations to ensure that placement was comparable. All four dummy comparison tests were conducted in the oblique configuration.

Table 2: Overview of test parameters

MODEL	MASS Kg	VELOCITY Km/h	IMPACT POINT mm
‘A’ WS	1428.8	32.61	12 right
‘A’ ES-2re	1429.9	32.54	0
‘D’ WS	1752.1	32.7	7 right
‘D’ ES-2re	1771.5	32.99	18 right

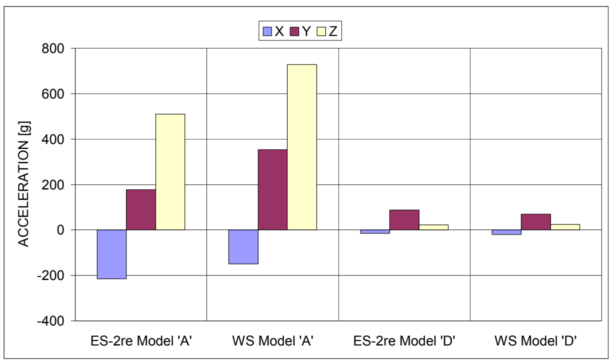

Figure 10: Comparison of paired vehicle cg accelerations.

Test mass, impact velocity and impact points were matched as closely as possible. The impact point measurements shown in Table 2 reflect the distance from the intended target. For example in the test of Model ‘A’ with the ES-2re the intended vehicle target was struck, however in the test with Model ‘D’ the actual impact point was 18 mm to the right of the intended location.

Figure 10 illustrates a comparison of the accelerations measured at the cg of each vehicle. Both tests of Model ‘A’ had comparable responses in all three axes. The large vertical acceleration recorded for the Model ’D’ test with the WS was actually due to the towing cables striking the undercarriage of the vehicle.

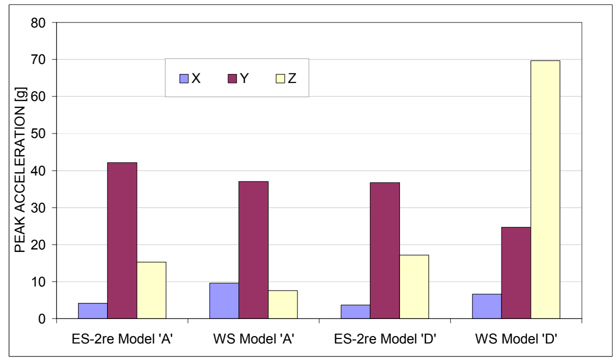

Figure 11: Comparison of peak head accelerations measured in the WS and the ES-2re.

Head responses shown in Figure 11 indicate that for the vehicle equipped with an effective side curtain (Model ‘D’) the translations are comparable for both dummies. In the absence of head protection, however the WS motion surpasses that of the ES-2re in both the lateral and vertical directions.

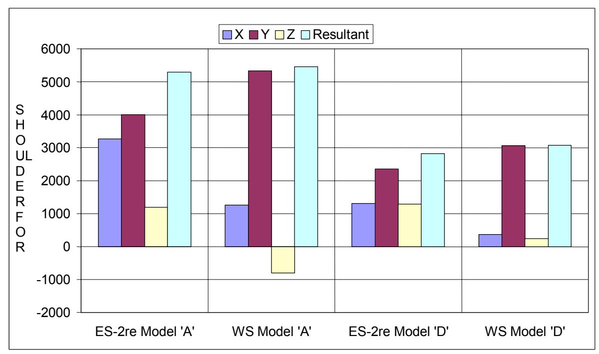

Figure 12: Comparison of peak shoulder force measured in the WS and ES-2re.

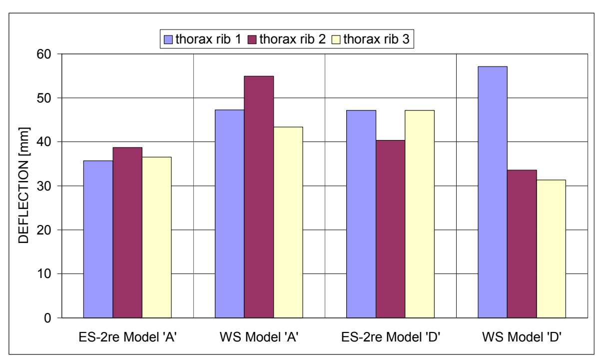

Figure 13: Comparison of peak thoracic rib deflections measured in the WS and ES-2re.

The previous test results indicated that for the WS dummy, shoulder, thorax and abdominal response were influenced by the impact location and airbag interaction with the arm. The results obtained from the comparitive dummy testing help to quantify the effect that dummy design, specifically shoulder design, can have on shoulder and thoracic rib responses. Figure 12 illustrates the components and resultant shoulder force measured in both dummies. It should be noted that while the resultants are equivalent, the components of force are quite different for the ES-2re and the WS. In Model 'A' for example, the ES-2re longitudinal force component is almost equal to the lateral component, suggesting that the peak load is being transmitted at an angle aproaching 45 degrees. The peak value of the longitudinal force in the ES-2re is three times the magnitude of the longitudinal forces measured in WS. In contrast, the WS shoulder is characterized by a predominantly lateral force component. A similar observation can be made in Model 'D' where the ES-2re shoulder response is characterized by strong longitudinal and vertical components whereas the WS shoulder response is again predominantly lateral. The measured shoulder deflection for WS attained the maximum excursion of 70 mm in both Models 'A' and 'D' signaling the location of an important load path at the shoulder complex.

Deflections for the upper, mid and lower thoracic ribs are shown in Figure 13. In Model 'A' the ES-2re deflections were characterized by a flat profile, ranged from 36 mm to 39 mm and were all lower than the corresponding WS rib deflections. In Model 'D' the first and third ribs of the ES-2re deflected 47 mm while the centre rib deflected marginally less at 40 mm. In WS the first rib tracked the shoulder and deflected 57 mm while the remaining lower ribs deflected between 31 mm and 36 mm. Based on the combined load and deflection measures it appears that in Model 'D' the load was transferred primarily through the shoulder and first rib, essentially sparing the remaining ribs of significant contact with the door. While the deflections measured in the ES-2re ribs were elevated it was not able to localize the load path.

The components and resultant lower spine (T12) accelerations for the ES-2re and WS are shown in Figure 14. In Model 'A' the WS accelerations are lower than those of the ES-2re whereas they are equivalent in Model 'D'. In all cases the resultant accelerations fall below the proposed limit of 82 g cited in the Notice of Proposed Rulemaking.

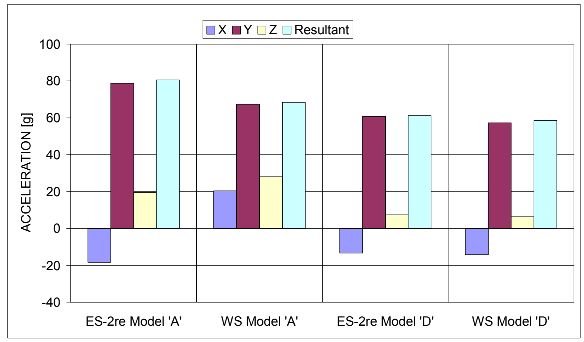

Figure 14: Comparison of T12 lower spine acceleration measured in the WS and ES-2re.

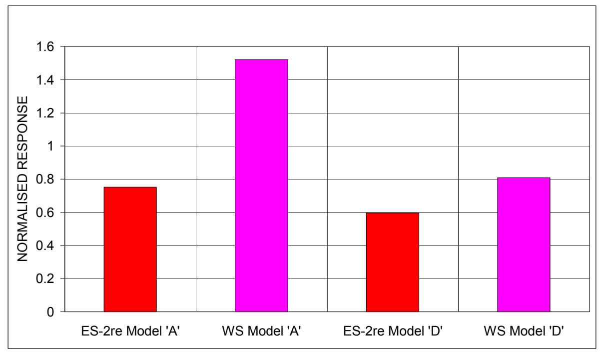

Figure 15: Comparison of the normalized abdominal responses for the WS and ES-2re.

Abdominal response in the ES-2re is measured with 3 load cells located in the anterior, mid and posterior pelvic cavity. In the WorldSID abdominal injury risk is determined from two abdominal rib deflections. Figure 15 compares the ES-2re abdominal force response normalized to the NHTSA Notice of Proposed Rulemaking abdominal injury criterion of 2,500 N. The WS response represents the maximum abdominal rib deflection normalized to 42 mm. Though injury criteria have yet to be specified for WorldSID abdominal responses a value of the order of 42 mm of deflection is anticipated. Based on the normalized responses of Figure 15, the ES-2re predict an acceptable level of injury risk for both Model 'A' and Model 'D'; the WorldSID rib deflections however, predict an unacceptable level of abdominal injury risk for Model 'A' where the maximum deflection, occuring in rib 2, surpassed 60 mm. Indeed it appears that the ES-2re is not sufficiently sensitive to differentiate between an aggressive armrest and a more compliant armrest combined with an effective thorax airbag.

DISCUSSION

Oblique and Perpendicular Tests. WorldSID responses were generally higher in the 15 degree oblique pole impact test when compared to a paired perpendicular pole test. Besides the obvious difference in orientation of the vehicle with respect to the pole, an oblique pole test differs from a perpendicular pole test in three ways:

a) The impact location is dependant on a plane drawn through the true cg of the dummy head and projected 15 degrees onto the curved surface of the vehicle door and therefore quite sensitive to dummy positioning;
b) The impact point is shifted forward of the perpendicular impact point by a distance of approximately 130 mm.
c) The impact energy is 2% higher due to the increased impact velocity. However when combined with test track accuracy, oblique pole tests were up to 10 % higher in this small sample.

The analysis of the vehicle acceleration response describes an impact event principally characterized by a lateral component of force suggesting that the approach angle alone is not sufficient to cause observable differences in the vehicle motion. Dummy kinematics are nevertheless affected by the three differences cited above. Video analysis and accelerometer data suggest the occurrence of a small but important forward motion of the dummy toward the impact point. This displacement influences the location of head strike as well as the exposure of the shoulder and thorax ribs. In the Model 'B' comparison for example, the impact point was situated 132 mm forward, which corresponded to less than a 20 mm shift in the head contact point and was just enough to place the head beyond the protective limits of the curtain. The forward motion added to the inertial loading of the dummy and placed the chest in an area of greater intrusion.

In the interest of future harmonized side impact test protocols it may be advantageous to consider a perpendicular pole test with an impact location defined by a specified distance forward of the dummy head CG. This way the complexity of alignment is removed.

The kinematics of the dummy arm and shoulder in Model 'C' were sufficiently unique to warrent further study. At present, little is understood of the interaction between an inflating thorax bag and the arm (human or otherwise) in the crash environment. Is it possible that the airbag contribute to injury by exposing the chest? Would a human arm stay in place during the loading phase and protect the chest? The need for in-depth field accident investigations and further laboratory crash testing is clear.

WorldSID and ES-2re Responses

Vehicle impact conditions and acceleration responses were sufficiently comparable to assume that the paired tests were equivalent and amenable to the comparitive analysis of dummy responses. Important differences were observed in the shoulder responses of the ES-2re, designed to rotate out of the way when struck, and the compliant WorldSID shoulder. The components of force measured at the shoulder of the ES-2re describe a combined loading characterized by equivalent longitudinal and lateral forces whereas the WorldSID forces are purely lateral. The non-compliant shoulder of the ES-2re is seen to lead to a rotation of the thorax, displacing the side of the dummy inboard. This inherent rigidity of the shoulder was observed to cause a reduced excursion of the head when compared to the WorldSID head kinematics. The rotation of the chest was also responsible for altering the deflection pattern of the ribs, resulting in lower rib deflections that were evenly distributed across the three ribs. In the case of WorldSID the shoulder flexes and shrugs and stabilizes in position to transmit the lateral load through the thorax.

Comparative tests of the ES-2 and ES-2re carried out within the WorldSID Task Group activities found that the oblique test configuration led to reduced rib deflections when compared to the perpendicular configuration. Simulations carried out by Subaru in support of the IHRA side impact working group actvities suggest that the performance of the ES-2 is more sensitive to the location of the impact point than to the angle of impact. This finding is consistent with the findings reported for the oblique and perpendicular comparison with WorldSID.

The measurement capability of the WorldSID shoulder rib in combination with the rib deflection measurements of the three thoracic ribs and two abdominal ribs provides a continuous region of measurement capability making it possible to identify and localize load paths, an advantage not available in the ES-2re. This was demonstrated in the responses of Model 'D' where an important load path present at the shoulder went undetected by the ES-2re. The spine accelerations at T1 and T12 the upper and lower levels of the spine, respectively were insensitive to the shoulder loads described.

In the pelvis the load plates of the ES-2re were unable to detect abdominal penetrations caused by the intruding armrest of Model ‘A’. Video analysis of the pole tests show evidence of the intruding door penetrating into a region of the ES-2re dummy abdomen, above the pelvis, that is devoid of instrumentation. The corresponding region in the WorldSID is encompased by two abdominal ribs and instrumented by IRTRACCs and accelerometers. As a result abdominal deflection response in Model ‘A’ signaled the potential risk of serious injury to the abomen where the ES-2re did not.

CONCLUSION

Three paired pole tests were conducted to compare the differences between a perpendicular pole test and a 15-degree oblique test. Vehicle acceleration responses were not significantly affected by the 15-degree angle though the intrusion profile and maximum residual deformation were exacerbated by the forward shift of the impact point and the increase in impact energy.

The WorldSID head was observed to display slightly greater forward displacement in the oblique tests prior to contact with the curtain or pole. Shoulder, thorax and abdominal rib deflections were greater in two of the three oblique tests conducted. The forward shift of the impact point, which was up to 135 mm forward of the seating reference point in the oblique tests, played a significant role in the overall response of the dummies. In the single paired test where the perpendicular test responses were greater than the corresponding oblique condition the seat mounted thorax airbag deployment was found to adversely affect the protection of the ribs by rotating the arm upwards and exposing the chest to the intruding door.

Further testing is necessary to investigate the interaction between complete airbag deployment and the dummy arm during the loading phase of door intrusion. The feasibility of replacing the angled pole test with a perpendicular pole test shifted forward may well be a viable option for a world harmonized pole test procedure.

Two paired oblique pole tests were conducted to compare the WorldSID and ES-2re responses. The inherently stiff shoulder design of the ES-2re caused rotations of the shoulder and thorax, influencing both the head trajectory and the deflection pattern of the thorax ribs. In contrast the WorldSID shoulder design responded in a humanlike fashion, shrugging and deflecting to a maximum stroke of 70 mm.

The ES-2re failed to identify principal load paths through the shoulder and elevated intrusions in the abdomen producing dummy response values below the proposed injury criteria. Further investigation should be conducted to more completely quantify the ES2-re limitations prior to adopting this dummy into regulation.

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The opinions expressed and conclusions reached are solely the responsibility of the authors and do not necessarily represent the official policy of Transport Canada.

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APPENDIX A

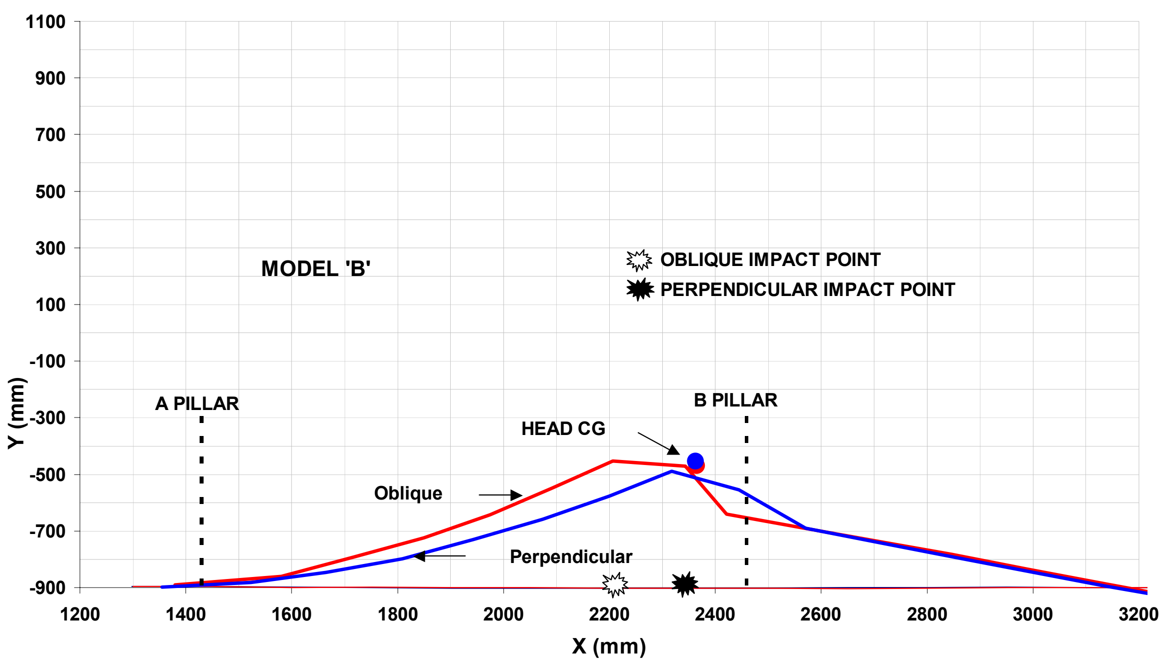

Figure A1 1: Residual deformation measurements for Model 'B' in the oblique and perpendicular pole tests.